Quantifying Pest-Caused Forest Depletion Using Geographic Information Systems and Database Technologies

J.M. Power and S.P. D'Eon
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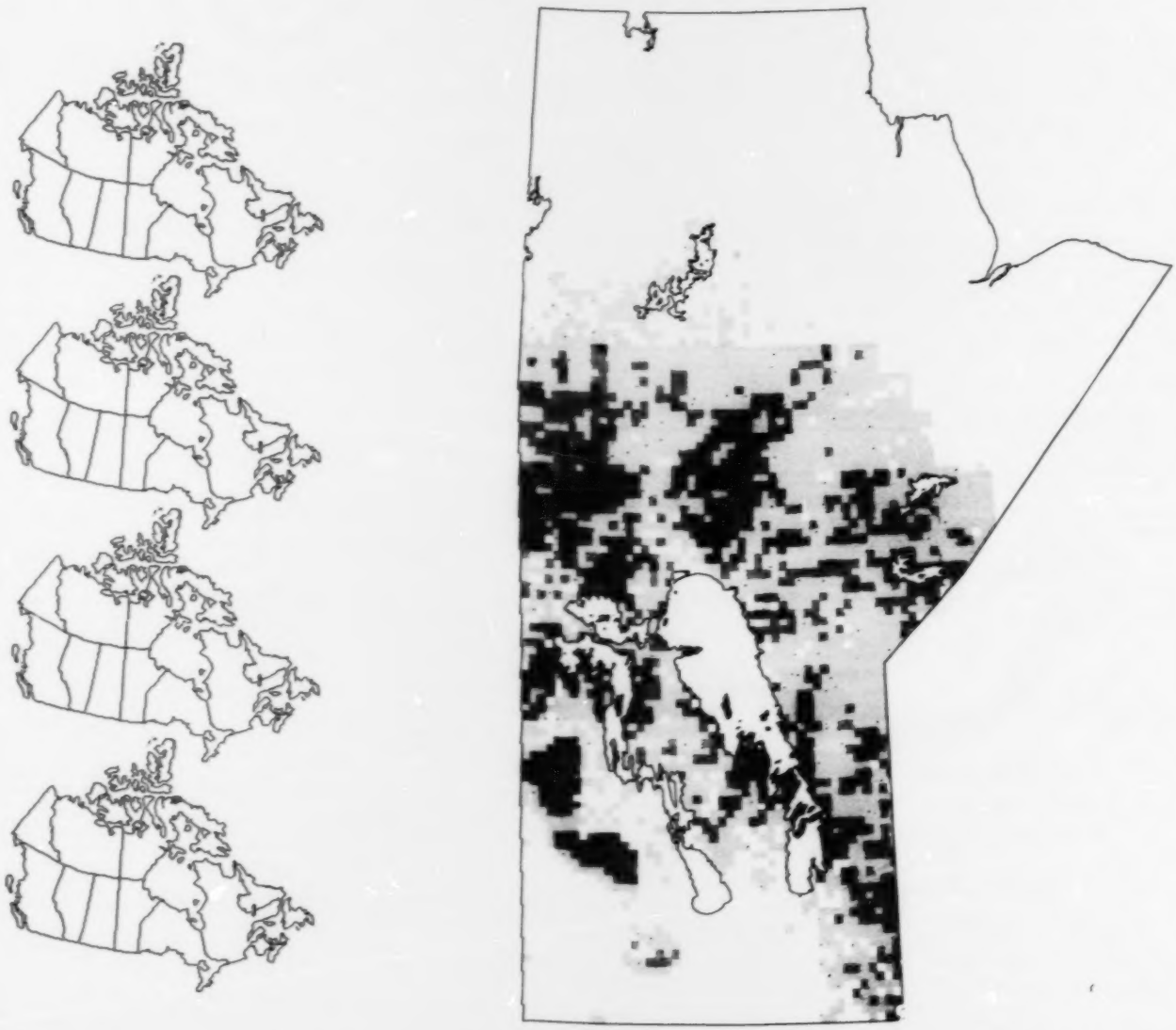

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Abstract

An automated system was developed to facilitate national estimates of pest-caused forest depletions. The system uses a geographic information system (GIS) for processing pest infestation and forest inventory maps, and a relational database management system (RDBMS) for processing map attributes, depletion factors, and statistics. It uses the GIS to overlay pest infestation maps with forest inventory maps, and the RDBMS is employed to apply expert rules to select the appropriate part of the forest inventory deemed to be host to a pest. Similar sequences of pest infestation are grouped into impact classes to standardize pest activity levels. Expert rules estimate the percentage growth loss reduction and/or mortality a pest activity level has caused on a host forest stand. The resulting depletion estimates are output in tabular format and passed back to the GIS for map output. The system was tested in estimating spruce budworm (*Choristoneura fumiferana* (Clem.)) -caused depletions in Manitoba from 1982-1987.

The integration and use of geographic information systems and relational database management systems in depletion estimations is an example of how the burden of complex and laborious operations can be eased by computer processing and useful results obtained. The system offers benefits in national pest-caused depletion estimates by automating routine tasks, by using an open methodology that improves scrutiny and technology transfer to other agencies, and by standardizing data, terminology, and methodologies for comparing pest-caused depletions with changes in forest capital due to non-pest causes.

Résumé

Un système automatisé a été mis au point pour faciliter les estimations nationales du dépérissement des forêts. La présente méthode utilise un système informatique géographique (SIG) pour générer des cartes d'inventaire forestier et de déploiement des infections d'une part et un système de base de données relationnelles (SBDR) d'autre part. Avec ce dernier, on établit des attributs de cartes, des facteurs de dépérissement et des statistiques. La méthode fonctionne de sorte que les cartes d'infection sont superposées aux cartes d'inventaire forestier à l'aide du SIG. Le SDDR est utilisé pour appliquer des règles-experts qui peuvent déterminer la partie de la forêt la plus susceptible à une infection. Des séquences similaires d'infection sont regroupées dans une classe d'impact pour normaliser les niveaux d'infection. Les règles-experts estiment le pourcentage de perte de croissance ou celui de mortalité dans le peuplement hôte. Les résultats des estimations du dépérissement sont obtenus en forme tabulaire. Ensuite, ils sont reprogrammés dans le SIG qui génère les cartes. Le système a été testé en l'occurence d'un dépérissement causé par la tordeuse des bourgeons de l'épinette [*Choristoneura fumiferana* (Clem.)] au Manitoba entre 1982 et 1987.

L'intégration des SIG et des SBDR pour estimer le dépérissement est un exemple qui prouve comment les opérations complexes et coûteuses peuvent être simplifiées à l'ordinateur et obtenir des résultats utiles. Le système offre les avantages en automatisant les tâches routinières pour les estimations nationales de dépérissement causé par des infections. Ces avantages se révèlent d'une méthodologie ouverte qui améliore la qualité et le transfert de technologie à d'autres agences en normalisant les données, la terminologie et les méthodes pour faire la comparaison entre le dépérissement causé par des infections et le changement de réserve forestière causé par d'autres facteurs.

Introduction

In order to understand the dynamics of forests at large geographic scales - regional, national, and global - attempts are being made by forestry agencies to quantify influences on the forest capital (Honer and Bickerstaff 1985). The Forest Insect and Disease Survey (FIDS) of Forestry Canada produces periodic statistics on one such influence, forest depletion by insects and diseases in Canada. The impact of forest pests is poorly understood at large geographic scales mainly because estimates have been heavily subjective. Moreover, national estimates have been infrequent, with the most recent figures for Canada being those published in 1982 for the period of 1977-81 (Sterner and Davidson 1982). In the past, the estimation process was well designed but limited by manual calculations. Combining all available data and knowledge on pest impact has been useful in deriving a best estimate but, without automation, the calculation procedures were overwhelming. In this paper we describe an automated system that was developed to facilitate national estimates of forest pest impacts.

Depletion in this paper refers to the reduction of timber volume attributable to the destructive activities of an insect or disease. The reduction of timber volume occurs through pest-induced tree mortality and growth loss. Growth loss (also called 'unrealized growth') refers to the pest-caused reduction of expected tree growth. Depletion estimates do not consider changes in stand density or stand composition that a pest infestation may initiate. The synergestic effect of more than one pest or other stresses on a stand is also not considered; each pest is treated separately. As well, the biological and economic impacts on current or future timber supply are not considered.

Estimates for depletions that occurred during the 1980s are being compiled by regional FIDS units for the following pests: spruce budworms, jack pine budworm, hemlock looper, mountain pine beetle, spruce bark beetle, other bark beetles, aspen defoliators, miscellaneous defoliators, dwarf mistletoe, hypoxylon canker, decays, root rots, and miscellaneous diseases.

The system developed to support depletion estimates uses the best available data on the location and extent of insects and diseases, the corresponding forest inventory, and the effects of each pest on growth and mortality of each host tree species. It then provides the processing power to the user to run through various depletion scenarios to provide regional timber depletion estimates. Assumptions are explicitly stated, debated by other pest experts, and easily revised with this automated system. The user is thus able to devote more time to improving the knowledge base rather than to mundane data processing tasks.

The system uses a geographic infomation system (GIS) for processing of infestation and forest inventory maps, and a relational database management system (RDBMS) for processing of map attributes, depletion factors, and statistics. Although primarily intended to work with pests whose areas of infestation have been located and mapped, the system has been applied to pests and diseases that are considered to be homogeneously distributed across forest regions, such as root rots.

This report describes the data sources, processing techniques, and products of the pest depletion estimation system. The results of using the system for estimating spruce budworm depletion in Manitoba are presented as an example. The implications of using the system for national estimates are summarized. Technical specifications for the system are available from the authors on request.

Infestation Maps

To estimate pest-caused depletion during a time period it is necessary to know the location and extent of pest infestations. The primary source of infestation maps are those prepared by FIDS and some provincial agencies using aerial sketch map techniques. Flights must be made after damaging pest activity has ceased for the year in order to observe the full extent of the current year's infestation. The observer does not view actual pest activity but sees the resultant damage to the forest, usually defoliation. In the short period the aircraft passes over each site, the observer distinguishes the severity of the infestation as well as the variations in pattern of the visible indicators of pest presence. Observations are then transferred to a national topographic series (NTS) map. Map scales of 1:125 000 or 1:250 000 are commonly used. The observer must register the

infestation areas onto the map using visible geographic features such as lakes and roads that are represented on the map. The accuracy of aerial sketch mapping must be considered when these maps are used in quantifying depletion.

The severity classification levels used to record visible pest activity vary across regions and pests. With spruce budworm, for example, broad levels of defoliation have been described as "moderate to severe" where defoliation exceeds 25-35% but, on some occasions, spruce budworm defoliation classes have been described as light, moderate, severe, or even "light to moderate" (Sippell 1983). Rather than force these classes into a standardized class system, their original meanings were retained.

The GIS is used to digitize the infestation polygons (the boundaries of each patch of infestation) from the sketch maps, and to attach their severity classifications. All maps required for depletion estimation for each pest are loaded and retained in a map database as a set of "coverages". The set of maps for each pest are digitally overlaid in the GIS to produce a union of all infestation polygons for each year. The resulting composite map retains features from all years representing the cumulative activity of the pest over the time period. Each new polygon resulting from the union will carry an attribute identifying its pest history as a sequence of severity classes. Aside from its use in depletion estimation, overlaying procedures can be used to analyze other features in an outbreak. For instance, if each set of maps were overlaid, starting with the first year of an infestation using a cut-and-paste process, the product would depict the annual progress of an outbreak.

From aerial sketch maps for each year, an historical picture of the life of an outbreak can be pieced together; specifically, a map chronology can show how infestations expand and contract. A composite of a number of years of infestation maps can be used to calculate the cumulative impact of an infestation over a period. These derived maps will supply the necessary temporal and spatial information on the pest situation to estimate depletion.

Forest Inventory

The timber volume of forests affected by pest infestations must be known to estimate pest-caused depletions. All provincial forest inventory agencies produce maps of forest stands with an association to timber volumes by tree species. Although most of these agencies are making good progress in loading the spatial characteristics of stands into GISs, digital stand data is far from complete. This prevents their use for topological overlaying with other thematic data, such as defoliation, for all regions. However, map sheet grids with aggregated timber volume data are available in digital form through Canada's Forest Inventory database (1986 version), Canadian Forest Resource Data System (CFRDS), Petawawa National Forestry Institute, Forestry Canada.

Provinces contribute to the national forest inventory every five years with their most up-to-date data. The most recent version is Canada's Forest Inventory database (1986 version). It provides a standardized national view of Canada's timber resources, which is important when factors of forest change, such as pest-caused depletion, are to be expressed meaningfully in relation to each other and to other forest inventory capital changes.

Canada's Forest Inventory 1986 is a management inventory containing stand classifiers, timber volumes, and stand areas standardized from 37 source inventories. The characteristics of the source inventories determine which classifiers and volume fields have data reported. There are numerous administrative and biological classifiers within Canada's Forest Inventory 1986 of which three have been selected for use in depletion estimates: maturity, forest type, and predominant genus. The maturity classifier is reported for 86% of the area inventoried and has not been estimated for areas where it is not reported (Gray and Nietmann 1989). The forest type classifier is reported for 100% of the area inventoried. The predominant genus classifier is reported for only 49% of the area inventoried and, as part of the depletion exercise, has been estimated whenever possible using the species group volumes. Where the classifier was not estimated the definitions of the three selected classifiers are as follows:

1. MATURITY - a qualitative expression of stand development based on the known stand age or on a management opinion.
2. FOREST TYPE - based on whether

the species composition of a stand is predominantly softwood, hardwood, or mixedwood.

3. PREDOMINANT GENUS - the most abundant genus in the cover type.

Canada's Forest Inventory 1986 reports timber volumes as volume per hectare in 19 fields that represent a single species, a species group, a genus, or a forest type. The use of each field is specific to a source inventory. A complete description is contained in Gray and Nietmann (1989). The Appendix contains a summary of the 19 fields.

The single species fields are appropriate for depletion estimation but the species group fields may not be appropriate. Timber volumes for different tree species grouped together should not be used because a pest may affect each tree species in the group differently. For example, Canada's Forest Inventory 1986 reports black spruce and red spruce as a single field whereas black spruce is known to be more resilient to spruce budworm attack than red spruce (MacLean et al. 1984). In some instances the second tree species in the group may not be a host to the pest at all. No modifications to the inventory were made to overcome this problem.

Approximately one quarter of the area inventoried in Canada has volume reported to the forest type level only (Gray and Nietmann 1989). Volume is reported to the genus level on a further 9% of the area inventoried. As part of the depletion exercise, these two summary level fields were broken down into species level fields whenever possible. Statistical corrections were obtained from inventory data for similar strata that contained a more detailed inventory. These corrections were then used to proportion the forest type and genus level fields into the appropriate detailed fields.

For example, Canada's Forest Inventory 1986 for Saskatchewan comes from seven source inventories, two of which report to the forest type level only and a third does not report timber volume since it is from a National Park. Data from the four more detailed source inventories were stratified by Rowe's forest section, maturity, predominant genus, forest cover type, and stand volume class (multiples of 50 cubic metres per hectare). The percentage volume for 10 detailed timber volume fields was then calculated for each stratum. This lookup table was used to split the two forest type level inventories proportionally into 10 detailed timber volume fields. The inventory for the National Park was estimated by dropping the 50 cubic metre per hectare stand volume class and redoing the stratification to get the average volume per hectare.

Canada's Forest Inventory 1986 is spatially divided into over 43 000 map sheets or cells, most of which are about 100 square kilometres. The cell grid covers the forest land area of Canada but some cells contain no forests (eg, agriculture areas). All stand data are spatially summarized to the cell level, so it is impossible to locate any spatial features within a cell. The timber volume within a cell must be treated as homogeneously distributed within the cell although this is often not the case.

The volume reported within each cell is aggregated by unique combinations of the three classifiers (maturity, forest type, and predominant genus) that were selected for use in pest depletions. Each record represents one or more forest stands with the same combination of classifiers. This type of aggregation does not retain the original detailed stand volumes which may be useful in depletion estimation. For example, if a pest required a minimum threshold host density of 15 cubic metres per hectare to maintain its population, this requirement could not be satisfactorily tested with aggregated data. If a cell had nine 100-hectare stands each with a host density of 10 cubic metres per hectare, these would not be hosts. If the same cell had a tenth 100 hectare stand with a host density of 75 cubic metres per hectare, aggregation would result in an average host density of 16.5 cubic metres per hectare for the 10 stands (calculated as (9x100x10+1x100x75)/1000). Aggregation causes the 10 stands to be processed as a single stratum of 1000 hectares. The entire 1000 hectare stratum would be erronously considered host under the example minimum threshold rule. Host rules using a density condition will not be used as part of the depletion estimation system because they cannot be properly tested with aggregated forest inventory data.

Ideally, in any depletion exercise, one should start with the inventory at the start of a pest outbreak and then annually adjust the inventory with the pest effects as well as all other growth (gain) and loss effects. At any time thereafter, the depletion for any period (i.e. 1982-87) could

be simply found using the annually adjusted inventory. Unfortunately, we do not yet have data of this accuracy and timeliness. A major problem with Canada's Forest Inventory 1986 is the variation in age of the provincial inventories, which ranges from zero to 20 years. Inventory age is an artifact of provincial inventory processes, where reinventory occurs on a cyclical basis, frequently 10 years but, occasionally, 20 years. Depending on the technological and budgetary resources available within each province, attempts are made to keep inventories up-to-date, especially for the major visible changes and with calculations of age and growth. Canada's Forest Inventory 1986 is less than 10 years old on the average, and it can be assumed that it represents the forest as it was in 1976. We have assumed that the 1986 inventory is appropriate for depletion estimation for periods between 1976 and the present.

For growth loss calculations, the current annual increment in cubic metres per hectare per year is required for each host tree species, preferably broken down by the same strata used for inventory. Unfortunately this type of growth data is not available as part of the CFRDS. Instead, we used the growth rate figures of Bickerstaff et al. (1981) who reported the estimated mean annual increment at maturity for unmanaged natural stands of average stocking for all of Canada. They stratified their figures by province and forest section (Rowe 1975), except for British Columbia which was stratified by inventory biozone. Bickerstaff et al. (1981) did not provide a breakdown by maturity, forest cover type, predominant genus, or tree species.

The use of Bickerstaff's growth figures for depletion can cause an overestimate of growth loss in some depletion calculations and an underestimate in other cases. Overestimates occur where the host rules identify stands or tree species that have a current annual increment that is much lower than the average mean annual increment at maturity. Overestimates would also occur where the host rules select only the slower growing tree species within a forest section. Underestimates occur where the host rules identify stands or tree species that have a higher current annual increment than the average mean annual increment at maturity. No adjustments were made within the pest depletion estimation system to account for these anomalies.

Host Inventory

The portion of the forest inventory considered susceptible to any level of attack by a specific pest must be identified so that it can be extracted for the depletion estimation. Through research and expert knowledge, a set of rules can be derived that describes the host inventory of a pest. In the form of rules, host susceptibility can be readily described by one researcher and be understood and debated by others. Host rules can be specific to a region, a province, or a more detailed geographic area such as a forest section. For example, by indicating thresholds of stand composition within which a tree species may be considered a host, Gross (1985) described the host inventory in Ontario that is susceptible to spruce budworm. Based on his description we derived a set of host rules:

- For the balsam fir working group* all the black spruce, white spruce, and balsam fir trees are hosts.
- For the spruce (black and white spruce) working group all the white spruce and balsam fir trees are hosts.
- For the spruce working group all black spruce associated with balsam fir are hosts.
- For the jack pine working group there are no hosts.
- For pure black spruce stands there are no hosts.
- For all other working groups where the combined total of balsam fir, white spruce, and black spruce associated with balsam fir is greater than 10% of the total, half of these trees' volumes are host.

The following is an interpretation of these six host rules into four explicit statements that can be used to extract host inventory data from Canada's Forest Inventory 1986:

- Where the predominant genus is "fir" (in Ontario this will be balsam fir only), the percentage volume by species that is considered to be host

*Working group - An aggregate of stands, including potential forest areas assigned to the category, having the same major species (Armson et al. 1980). This is further defined for photointerpretation purposes as an aggregate of trees where one species occurs alone or as the predominant species in a mixture (OMNR 1987).

is: white spruce, 100; black spruce, 100; and balsam fir, 100.

- Where the predominant genus is "spruce" (in Ontario this will be white and black spruce with an insignificant amount of red spruce) and where the black spruce volume is less than 90% of the stand composition, the percentage volume by species that is considered host is: white spruce, 100; balsam fir, 100; and black spruce, 100 x balsam fir/total stand volume.
- Where the predominant species is jack pine (where jack pine has the predominant volume in the "pine" predominant genus category), no species are host.
- Where the predominant genus is one of the other genera (not "fir", "spruce", or the jack pine component of "pine"), and where the combined total of a) black spruce volume x balsam fir volume/total stand volume, b) white spruce volume, and c) balsam fir volume, is greater than 10% of total stand volume, then the percentage volume by species that is considered host is: white spruce, 50; black spruce, 50 x balsam fir volume/total stand volume, and balsam fir, 50.

The data from one CFRDS cell is presented in Table 1 to illustrate the selection of host inventory. The cell has a total reported area of 9573 hectares of which 3962 hectares are inventoried productive forest land. Using the three selected inventory classifiers (maturity, cover type, and predominant genus) the forest inventory for this cell consists of the thirteen strata listed in Table 1.

Applying the host rules for spruce budworm to these 13 strata eliminated eight strata as non-hosts. The four strata with 'pine' as their predominant genus (strata # 3 to #6) were eliminated because they were principally jack pine stands as indicated by the percent jack pine column. The 'larch' strataum (# 2) was eliminated because the combined host volume was less than 10% of the total volume. Three of the 'poplar' strata (# 7, #9, and #10) were eliminated by the same rule as the 'larch' stratum. Approximately 12% (472 hectares) of the forest area was selected as host stands (combined area of strata 1, 8, 11, 12, and 13). The host rules extracted only 1.4% of the black spruce volume, 5.4% of the white spruce volume, and 15.1% of the balsam fir volume. The host inventory for this cell is shown in Table 2.

The host inventory contains both standing volume and growth data. Growth data is stored as the total volume increment per year for each stratum, not as volume per hectare per year. The host growth increment for a species within a strata is calculated as:

% host species volume * Bickerstaff's growth rate * strata area

Table 1. Selected inventory parameters for a CFRDS cell (all volume figures are gross merchantable cubic metres)

#	Maturity	Cover type	Predom. genus	Area (ha)	Black spruce volume	White spruce volume	Balsam fir volume	% jack pine	% host
1	immature	soft	fir	20	36	54	108	7	80
2	immature	soft	larch	64	742	38	25	0	2
3	immature	mixed	pine	43	305	103	38	47	3
4	immature	soft	pine	2478	24284	3964	1486	69	4
5	mature	mixed	pine	13	123	15	10	47	2
6	mature	soft	pine	804	5949	643	321	85	1
7	immature	hard	poplar	13	15	63	24	4	7
8	immature	mixed	poplar	29	52	174	110	21	17
9	mature	hard	poplar	48	28	244	96	3	7
10	mature	mixed	poplar	7	16	39	14	27	6
11	immature	mixed	spruce	21	900	27	23	34	3
12	immature	soft	spruce	418	14630	83	167	12	2
13	mature	mixed	spruce	4	173	46	14	20	10
		Totals		3962	47253	5493	2436		

Table 2. Spruce budworm host inventory for a CFRDS cell (all volume figures are gross merchantable cubic metres)

Maturity	Cover type	Predominant genus	Tree species	Host volume	Host growth increment per year
immature	soft	fir	black spruce	36	4.8
immature	soft	fir	balsam fir	108	14.5
immature	soft	fir	white spruce	54	7.2
immature	mixed	poplar	black spruce	26	0.7
immature	mixed	poplar	balsam fir	55	1.5
immature	mixed	poplar	white spruce	87	2.3
immature	mixed	spruce	black spruce	18	0.3
immature	mixed	spruce	balsam fir	23	0.4
immature	mixed	spruce	white spruce	27	0.4
immature	soft	spruce	black spruce	573	19.0
immature	soft	spruce	balsam fir	167	5.5
immature	soft	spruce	white spruce	83	2.8
mature	mixed	spruce	black spruce	4	0.1
mature	mixed	spruce	balsam fir	14	0.1
mature	mixed	spruce	white spruce	46	0.4

where

$$\% \text{ host species volume} = \frac{\text{host species volume}}{\text{total strata volume for all species}}$$

This method of calculating host growth will introduce over- and underestimates whenever the current annual increment for the host species within a stand is not divided proportionally to the standing timber volume distribution. This type of over- or underestimate is in addition to the previously mentioned problems that arise from using Bickerstaff's (1981) growth data. An example of a calculation-induced overestimate of host growth is an overmature spruce component in a mature mixed wood stand that is host to spruce budworm. The host spruce component may make up a large proportion of the standing timber volume yet have a very low current annual increment due to it being overmature. Should the same stand have a sizeable young trembling aspen component and be infested with forest tent caterpillar, the host growth calculation would underestimate the current annual increment of the trembling aspen component.

Impact Classes

For a period of sequential years, the volume loss due to growth loss and mortality will depend on the pest history each stand has experienced. This history can be defined as a series of visible levels of pest activity recorded for each year. The infestation maps used in the pest depletion estimation process utilize six subjective levels of pest activity: NONE, LIGHT, LIGHT TO MODERATE, MODERATE, MODERATE TO SEVERE, and SEVERE. For example, a stand may experience the following series of defoliations for a 10-year period; LIGHT, NONE, MODERATE, SEVERE, SEVERE, MODERATE TO SEVERE, MODERATE, LIGHT TO MODERATE, NONE, NONE. This sequence would result in a certain amount of pest impact on the host trees. A 10-year period could have over 60 million possible combinations of pest activity levels. To facilitate depletion estimations, each sequence of defoliations can be assigned to an "impact class". Impact classes are assigned to reduce the number of growth loss and mortality factors and not to reduce the number of calculations.

Impact classes group together sequences of defoliation that cause a similar level of pest impact on host trees. When a pest has multiple hosts, one set of impact class assignments is made. Modification for the susceptibility of different hosts to a pest are made by varying the growth loss and mortality factors, not the impact classes. Also, host stand characteristics (ie. maturity, cover type, and predominant genus) are not considered when assigning impact classes. Each pest requires its own set of impact classes because similar levels of pest activity may have dramatically different levels of impact. For example, three successive years of severe defoliation by spruce budworm may be assigned an impact class of 'low'; yet three successive years of severe defoliation by hemlock looper may be assigned an impact class of 'very high'.

The same impact classes are used for both growth loss and mortality calculations. Growth loss is dependent on the pest activity in the current year as well as the cumulative effect from previous years. Mortality is dependent on the cumulative effect of pest activity over a number of years. In calculating mortality that has occurred during a particular reporting period, the pest history for a number of years previous to the reporting period must be used as well. For example, in order to determine the mortality caused by spruce budworm, the annual defoliation sequence for a period of 10 years may be necessary (MacLean and Ostaff 1989). The rules which assign impact classes to an infestation sequences will change if the length of the reporting period changes, as impact classes relate to the amount of pest impact within the reporting period only.

The assignment of impact classes, as devised by the authors, to various pest activity sequences is shown in the following example for spruce budworm. Ten years of defoliation are used, of which the last six years comprise the reporting period.

Impact Class	Level	Rule
0	none	Less than two consecutive years of moderate to severe defoliation.
A	very low	Two consecutive years or three out of four years of moderate to severe defoliation, with at least one year in the reporting period.
B	low	Four out of five years of moderate to severe defoliation, with at least two years in the reporting period.
C	medium	Five out of six years of moderate to severe defoliation, with at least two years in the reporting period.
D	high	Six out of eight years of moderate to severe defoliation, with at least three years in the reporting period.
E	very high	Seven out of ten years of moderate to severe defoliation, with at least three years in the reporting period.

For a six-year reporting period, the example sequence shown above (LIGHT, NONE, MODERATE, SEVERE, SEVERE, MODERATE TO SEVERE, MODERATE, LIGHT TO MODERATE, NONE, NONE) would be assigned an impact class of C as the rule "five out of six years of moderate to severe defoliation" is true and there are four years in the reporting period. The impact class rules serve only as a guideline and all impact class assignments can be reviewed and debated by system users. Infestations that show a declining sequence or periods of recovery from defoliation are usually assigned to lower impact classes than the rules state. Increasing sequences may be assigned to higher impact classes. Once finalized, the impact class assignments for a pest are used by all regions. The use of standard pest impact classes across the country eliminates pest activity as a variable, allowing system users to compare growth loss and mortality factors for the same levels of pest activity.

Growth Loss and Mortality

Throughout an outbreak period the impact of pest activity on host trees accumlates, causing reduction in annual growth and, in some cases, severe stresses that lead to mortality. The amount of growth loss and mortality depends on characteristics of the insect species or disease, and the severity and longevity of infestation. Growth loss and mortality also varies with characteristics of the host forest such as stand composition and maturity.

In this paper, discussion will be limited to depletion estimations for a recent period, excluding effects on future growth and yield. Historical patterns must be understood first before projections can be made on the long-term effects of pest activity. Further research and collection of data and knowledge on the effects of pest activity on growth and yield will be required before regional estimates of changes to future timber supplies can be done operationally.

Through experience and the results of impact plots, field staff and scientists can estimate the depletion that may occur on a host tree species from a given pest history. The accuracy of these estimates will vary with the availability of supporting research and knowledge. Nevertheless, the best estimates that are available will be used in quantifying depletion, with the expectation that further surveys and research will contribute to better estimates in future.

The relationship of depletion to tree species, stand types, and impact classes can be expressed as factors, functions, or rules. Factors express depletion as a percentage loss for a given forest stratum and pest condition. Functions express depletion as a relationship between variables which can be represented as a curve or formula. Rules express pest impact as a series of statements that can be utilized to quantify the amount of depletion.

Gross (1985) expressed growth loss for spruce budworm in Ontario as a percentage reduction in growth rate stratified by the number of years of moderate to severe defoliation and host species. For example, Gross's factors for balsam fir ranged from a 0% reduction for a single year of moderate to severe defoliation to a 100% reduction for seven years of moderate to severe defoliation. Development of factors for depletion are specific to each region and are the responsibility of the regional user.

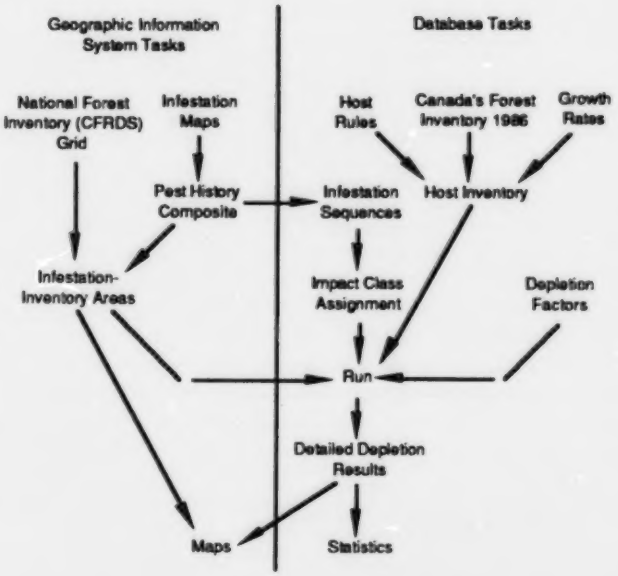

Figure 1. Depletion estimation system data flow.

Pest Depletion Estimation System

The pest depletion estimation system operates in two parallel processes using the ARC/INFO Geographic Information System and the INGRES Relational Database Management System. Most of the Forest Insect and Disease Survey units have access to an ARC/INFO GIS for map loading and processing. As well, all units have access to INGRES as part of the FIDSINFOBASE system for management of their insect and disease survey data (Power 1986). Figure 1 represents data flow for the depletion estimation system. The GIS tasks and the database tasks are done independently but in parallel, with data passing between the two software systems. Data passed from the GIS to the database must have the polygon identification numbers maintained throughout database processing so results can be passed back to the GIS for map output.

As described earlier in this paper, the GIS is used to digitize the infestation polygons from the sketch maps and attach their severity classifications. The set of maps for each pest for each year are digitally overlaid to produce a union of all infestation polygons by pest. The result is an infestation composite map for each pest that retains features from all years representing the cumulative activity of the pest over the time period. Each new polygon resulting from the union will carry an attribute identifying its pest history as a sequence of severity classes. The various sequences of severity classes are passed to the database so impact classes can be assigned.

The national grid coverage used by CFRDS for management and display of the national forest inventory is intersected with each infestation composite map by overlaying in the GIS. The result is a combined infestation - inventory map, where each new polygon has its own pest history and inventory grid cell identification. At this stage the polygon attributes have multiplied to the point where any further computer processing, all non-topological, is more efficiently done with the relational database management system.

INGRES stores data in tables using a relational model which dictates that all data within a table are unique to the key fields for that table and tables are related to each other through common keys. Numerous tables exist in the depletion estimation system to store data and calculations. Applications are developed in INGRES to accept entry of new data, to modify current data, to review data, and for initiating and controlling calculation runs. INGRES application options are selected by the user via computer menu screens. The system permits multiple users to work with the same tables and

data in the database during any session. System, table, and data access privileges are pre-assigned to each user.

During operational use, INGRES tables are loaded with the forest inventory area and volume data from Canada's Forest Inventory 1986, the forest growth rates from Bickerstaff et al. (1981), and the GIS-produced infestation - inventory data. Tree species and stand types are selected from the inventory according to the host rules, resulting in a target inventory table for each pest. The host rules are devised by the users and are specific to each region. Currently, the host rules must be manually translated into database queries for selections to be run. In future operations a natural language processor may be integrated with the system to automatically decipher common English statements into query statements.

A table for impact class assignments is filled with all the existing infestation sequences as passed from the GIS pest history composite. The users are able to review and debate these sequences and assignments and reach an agreement on a standard set of impact classes to be used for each pest.

The system currently accepts data on growth loss and mortality in the form of factors. Factors depict growth loss or mortality as a percentage reduction in growth or volume. A single INGRES table holds all factors for all pests, impact classes, stand types, host tree species, and geographic region. Users are able to compare their factors with others through an INGRES application.

When all data sets are loaded, the system is prepared for calculation of depletion. A calculation run is normally executed for one pest species within one geographic region at a time. The run procedure matches the infestation - inventory data with the selected host volume and growth data. The resulting infested host inventory is multiplied by the appropriate growth loss and mortality factor to produce a table of depletion estimates. These estimates are in a detailed form as they are stratified by host species, stand type, infestation polygon, and CFRDS grid cell. The results can be reviewed by the user, saved as a permanent or temporary file, or deleted. The whole estimation process can be rerun, with either revised factors for comparison with previous results or any updated data sets.

Statistics can be produced from the depletion estimate table by aggregating the numeric results into a format suitable for reporting, for example, regional summaries. Maps can also be produced by passing the depletion estimate data with their attached polygon identifying numbers to the GIS. The GIS can then aggregate adjacent polygons with similar characteristics to produce a regional depletion map showing growth loss and mortality.

Application example: Spruce budworm-caused growth loss in Manitoba, 1983-88

The pest depletion estimation system was used to estimate spruce budworm-caused growth loss in Manitoba for the six-year period 1983 to 1988. Infestation maps for the eight-year period 1981-88 were loaded and digitally overlayed in the GIS. The Manitoba part of Canada's Forest Inventory 1986 contains black spruce, white spruce, and balsam fir as individual fields. This inventory was loaded into the system. Two modifications to the host rules described earlier were made at the recommendation of the FIDS unit responsible for Manitoba. First, all forests of the hardwood cover type were not considered to be hosts. Second, the requirement that black spruce be associated with balsam fir in non-spruce/fir stands was dropped. These revised host rules were run and the resulting host inventory was passed back to the GIS for mapping (see Figure 2).

The impact classes were assigned to the sequences passed from the pest history composite to the database. The codes used to represent levels of defoliation within each sequence are as follows:

code	defoliation level
0	none
1	light
2	light to moderate/light and moderate
3	moderate
4	moderate to severe/moderate and severe
5	severe

The example sequence used earlier in this paper (LIGHT, NONE, MODERATE, SEVERE, SEVERE, MODERATE TO SEVERE, MODERATE, LIGHT TO MODERATE, NONE, NONE) would be represented as 1035543200.

The assigned impact classes differ from those given earlier in this paper because the data set contained only eight years of infestation maps rather than the recommended 10 years. The

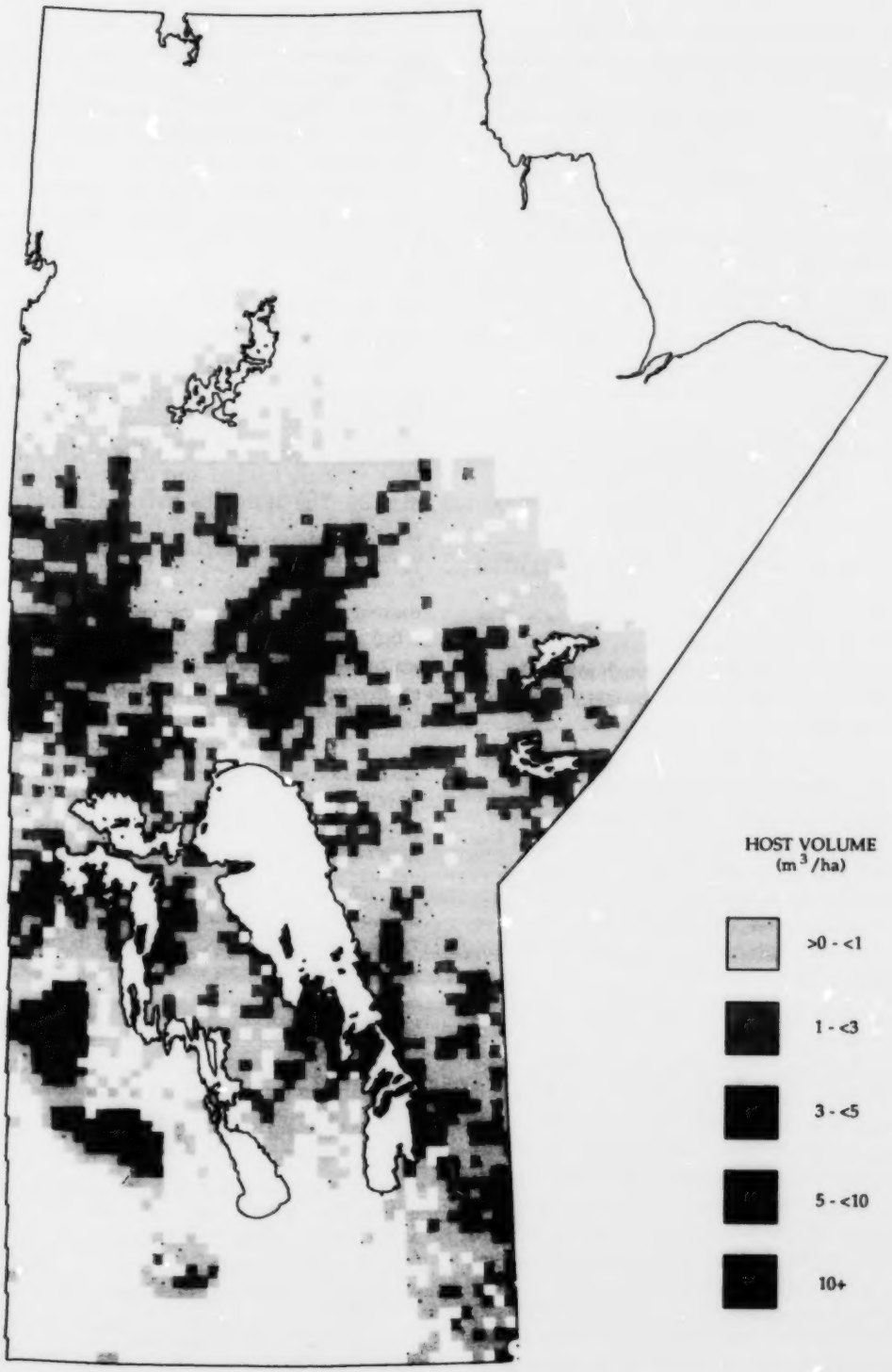

Figure 2. Forest Inventory susceptible to spruce budworm damage in Manitoba.

assigned classes and sequences are listed in Table 3.

Table 3. Impact classes used in estimating spruce budworm caused growth loss in Manitoba; 1983-88

Impact class	Defoliation sequences (1981-88)		
0 none	02000000	03000000	20000000
	22000000	23000000	30000000
	32000000	05000000	35000000
	45000000		
A very low	00000005	00000050	00005050
	00000500	00000505	00005000
	00050000	00050005	00050050
	00500000	00500005	00500050
	00500500	03500000	00050500
	05000005	05000050	00505000
	05000500	05000505	40500500
	35000500	45000500	40000500
B low	00000550	05505000	00050550
	00005055	00005500	00505050
	00050505	00055000	00500550
	00550000	00505500	00055050
	00550005	00550050	00000055
	05500500	05500505	05505050
	00500055	45500000	50550000
	00550500		
C medium	50550055	00005550	00550055
	00000555	00055055	00055500
	00555000	03500555	00550550
	05505005	05550000	45500500
	00500555	00550505	
D high	00505550	00505555	05555000
	00555500	05550500	05550505
	55550000	05550055	
E very high	00555550	00555555	05555055
	05555500	55555005	55555055

The impact classes were transferred back to the GIS to produce Figure 3. The areas in the medium, high, and very high impact classes were too small to map and thus are represented as symbols M, H, and V, respectively. The areas mapped in the various classes are summarized below:

impact class	area mapped (hectares)
none	884 542
very low	261 875
low	25 998
medium	6 857
high	2 513
very high	579
total area	1 182 354

Growth loss factors were generated by the regional FIDS unit for black spruce, white spruce, and balsam fir. These factors were stratified by maturity class and cover type and are factors for a six-year reporting period. Tables 4 to 6 show the growth loss factors used in this example. The calculation procedure was run using the data sets discussed above. The results were passed back to the GIS for mapping and the results are shown as Figure 4. No statistical summaries were prepared.

National Applications

The prime reason for developing the pest depletion estimation system was to assist the Forest Insect and Disease Survey in its depletion estimations for national reports. A number of FIDS units have prepared depletion statistics with this system for the national exercise covering the period 1982-87. The system has offered the following benefits to this and future endeavours:

1. Automation of routine tasks

Repetitive tasks such as map overlaying and processing of large databases have been automated, allowing FIDS staff to spend more time researching pest depletion factors and pest effects on trees. With automation, accuracy has been increased in situations where human judgement can introduce error. Examples of tasks where errors have been reduced are

- registration of infestation maps with each other and with the forest inventory,
- definition and measurement of polygons, and
- repetitious selecting, sorting, and calculations on thousands of records.

Estimates can be made at a finer level since datasets no longer have to be aggregated early in the process to make calculations manageable. With the automation of routine tasks, multiple runs can be made on the computer to test the effect of changing depletion factors, determine which factors are the most important, and incorporate new knowledge, inventory data, or infestation data. Because of the simplified process and time savings of the new system, the time interval between depletion exercises can be reduced to produce more timely results for forest managers.

2. Standardization

The system standardizes terms and methodologies so that data (inventory, pest distribution, host rules, factors) are directly comparable among regions. A standard structure is

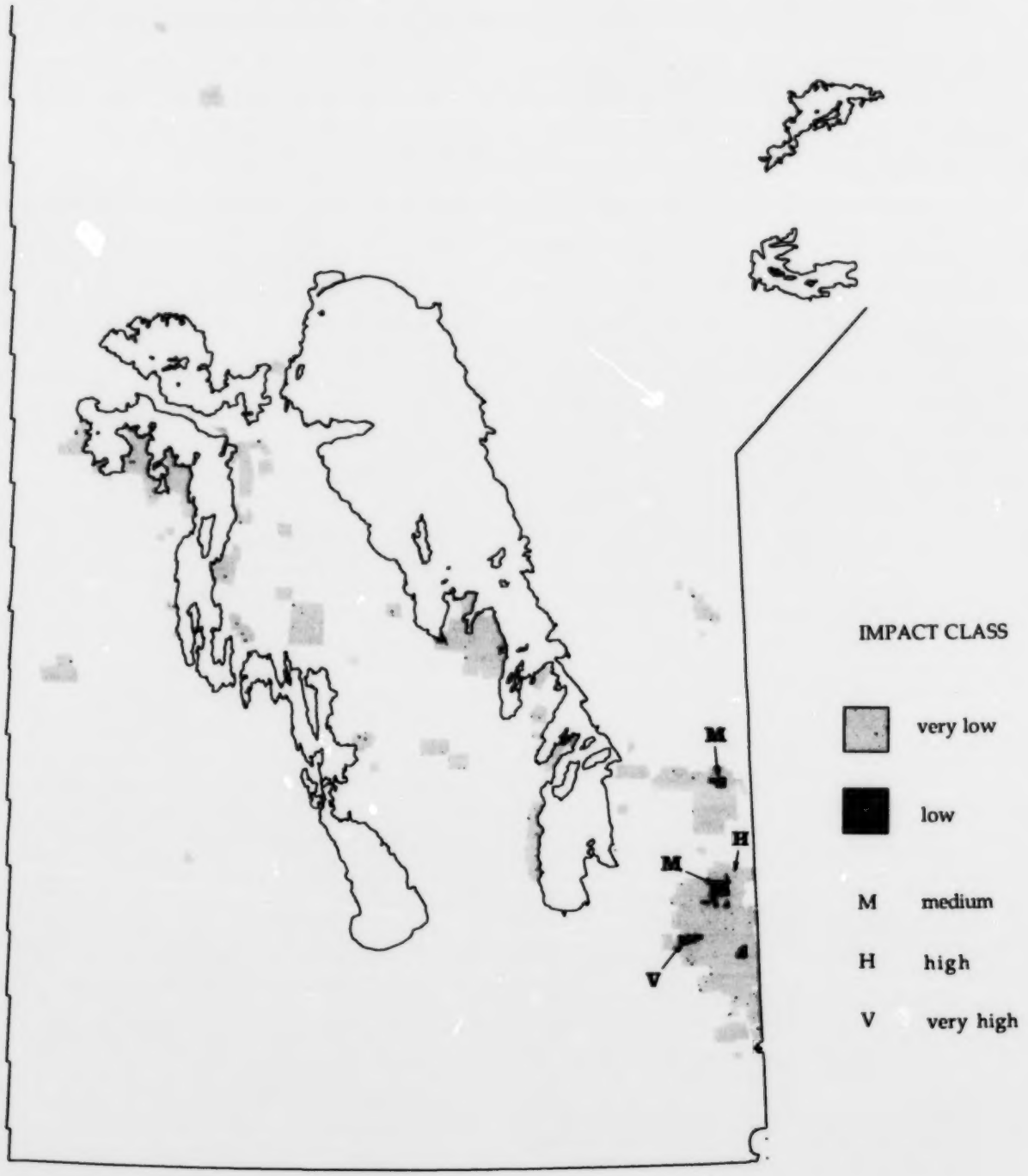

Figure 3. Spruce budworm activity level in Manitoba for 1983-88 reporting period.

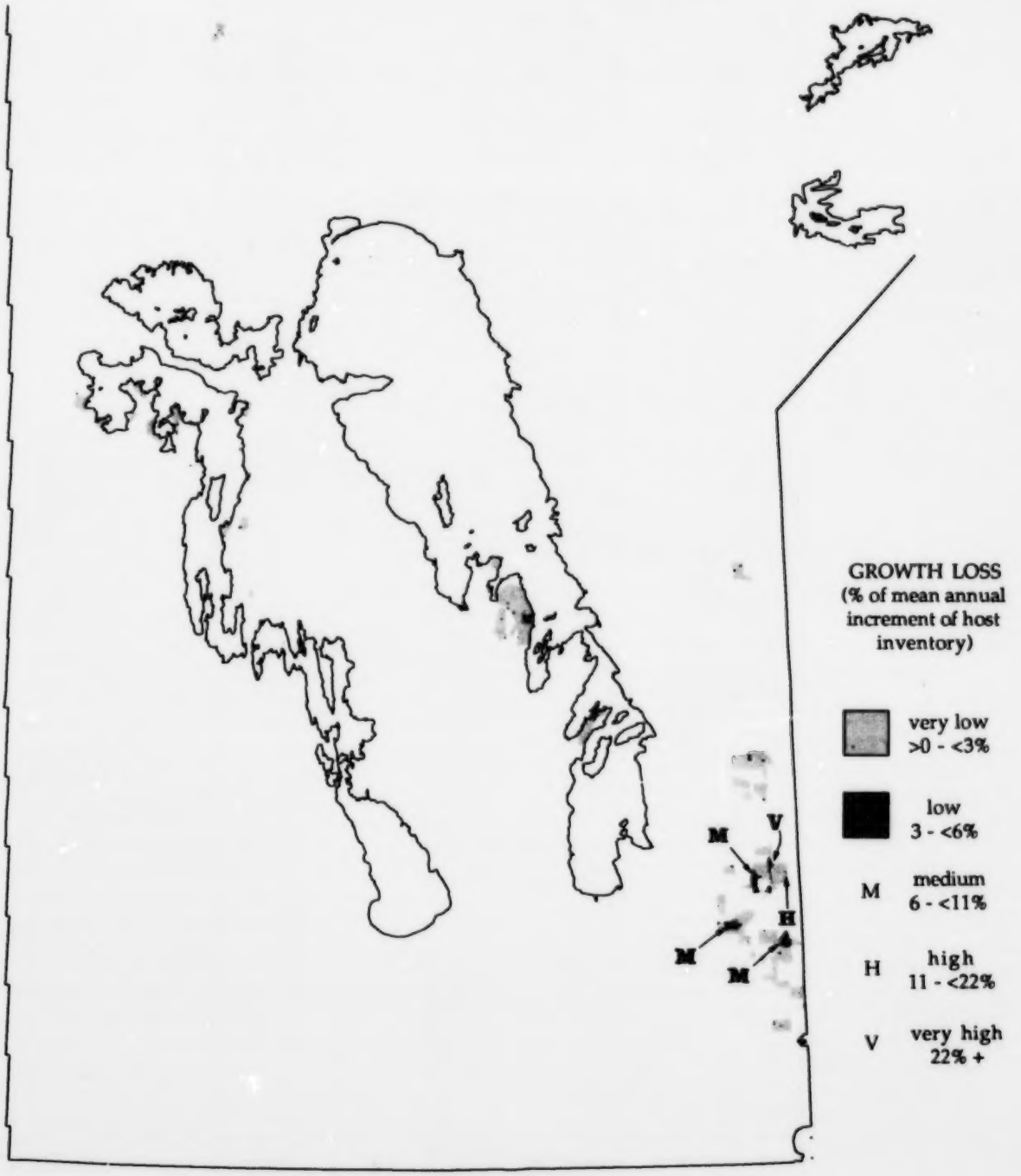

Figure 4. Percentage of growth lost due to spruce budworm (excluding mortality) for 1983-88 in Manitoba.

Table 4. Growth loss factors for spruce budworm in Manitoba host tree species: black spruce

Impact class	Maturity	Cover type	Depletion factor (%)
A	immature	mixedwood	0.0
A	immature	softwood	0.0
A	mature	mixedwood	2.0
A	mature	softwood	3.8
A	overmature	mixedwood	2.5
A	overmature	softwood	5.0
B	immature	mixedwood	2.5
B	immature	softwood	5.0
B	mature	mixedwood	4.0
B	mature	softwood	7.5
B	overmature	mixedwood	5.0
B	overmature	softwood	10.0
C	immature	mixedwood	5.0
C	immature	softwood	10.0
C	mature	mixedwood	7.5
C	mature	softwood	15.0
C	overmature	mixedwood	10.0
C	overmature	softwood	20.0
D	immature	mixedwood	7.5
D	immature	softwood	15.0
D	mature	mixedwood	10.0
D	mature	softwood	20.0
D	overmature	mixedwood	12.5
D	overmature	softwood	25.0
E	immature	mixedwood	10.0
E	immature	softwood	20.0
E	mature	mixedwood	12.5
E	mature	softwood	25.0
E	overmature	mixedwood	15.0
E	overmature	softwood	30.0

Table 5. Growth loss factors for spruce budworm in Manitoba host tree species: white spruce

Impact class	Maturity	Cover type	Depletion factor (%)
A	immature	mixedwood	0.0
A	immature	softwood	0.0
A	mature	mixedwood	3.8
A	mature	softwood	5.0
A	overmature	mixedwood	5.0
A	overmature	softwood	10.0
B	immature	mixedwood	5.0
B	immature	softwood	5.0
B	mature	mixedwood	7.5
B	mature	softwood	15.0
B	overmature	mixedwood	10.0
B	overmature	softwood	20.0
C	immature	mixedwood	10.0
C	immature	softwood	20.0
C	mature	mixedwood	15.0
C	mature	softwood	30.0
C	overmature	mixedwood	20.0
C	overmature	softwood	40.0
D	immature	mixedwood	15.0
D	immature	softwood	30.0
D	mature	mixedwood	20.0
D	mature	softwood	40.0
D	overmature	mixedwood	25.0
D	overmature	softwood	50.0
E	immature	mixedwood	20.0
E	immature	softwood	40.0
E	mature	mixedwood	25.0
E	mature	softwood	50.0
E	overmature	mixedwood	30.0
E	overmature	softwood	60.0

Table 6. Growth loss factors for spruce budworm in Manitoba host tree species: balsam fir

Impact class	Maturity	Cover type	Depletion factor (%)
A	immature	mixedwood	0.0
A	immature	softwood	0.0
A	mature	mixedwood	0.0
A	mature	softwood	0.0
A	overmature	mixedwood	0.0
A	overmature	softwood	0.0
B	immature	mixedwood	2.5
B	immature	softwood	10.0
B	mature	mixedwood	5.0
B	mature	softwood	15.0
B	overmature	mixedwood	10.0
B	overmature	softwood	20.0
C	immature	mixedwood	10.0
C	immature	softwood	20.0
C	mature	mixedwood	15.0
C	mature	softwood	30.0
C	overmature	mixedwood	20.0
C	overmature	softwood	40.0
D	immature	mixedwood	20.0
D	immature	softwood	40.0
D	mature	mixedwood	25.0
D	mature	softwood	50.0
D	overmature	mixedwood	30.0
D	overmature	softwood	60.0
E	immature	mixedwood	30.0
E	immature	softwood	60.0
E	mature	mixedwood	35.0
E	mature	softwood	70.0
E	overmature	mixedwood	40.0
E	overmature	softwood	80.0

used to calculate depletion estimates. Differences can be debated and reconciled. In some cases data from one region can be used to fill gaps in another region. The free exchange of information allows only the best data to be used in the system and points to areas where further research is needed. Overall results can be compared and analyzed on a national basis because each region uses the same methodology. Pest depletions can be compared with other losses of forest capital because a standard inventory has been used.

3. Improved methodology

The new process of assessing depletion is open and documented, allowing methods to be scrutinized, debated, and improved by other scientists. Components of the process can be adapted for use in future pest modelling exercises by FIDS and other agencies. The databases and methodology are in a form that can be transferred to other forestry agencies. The improved methodology should encourage regional FIDS staff to produce more frequent depletion estimates.

Discussion and Conclusions

Geographic information systems and relational database management systems are two of many types of applications software which can produce powerful results in data processing. The integration and use of these systems in depletion estimation represents an example of how the burden of complex and laborious operations can be eased by the computer and useful results obtained. The implementation of a standardized and structured process allows depletion results to be compared and analyzed to form part of the quantification of forest sector resources. By going through this process, existing gaps in knowledge on pest-caused growth loss and mortality become apparent giving direction to research in this field. The methodology used by the professional in estimating depletion can be preserved; only the mechanism changes.

With the increasing demand for regional, national, and global forest sector analysis, FIDS staff and other pest management professionals

have found it difficult to supply adequate and timely information on pest-caused timber depletion. This situation is being alleviated in part through the application of a well-structured system for capturing survey and research data and expert knowledge, and processing these into meaningful information.

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APPENDIX
Summary of Canada's Forest Inventory 1986 species volume fields

Field name	Description
black and red spruce	black spruce for all of Canada except Nova Scotia, New Brunswick, Prince Edward Island and Quebec where it is black and red spruce.
other spruce	white spruce for all of Canada with the addition of Norway spruce in Quebec, Englemann spruce in Alberta and British Columbia and sitka spruce in British Columbia.
fir	balsam fir for all of Canada except for British Columbia where alpine, amabilis, and grand fir.
Douglas fir	Douglas fir in Alberta and (two varieties) in British Columbia.
white pine	eastern white pine except for small area of British Columbia where field is for western white pine.
jack pine	jack pine in areas east of Alberta, lodgepole and jack pine in Alberta, and jack pine, lodgepole pine, and shore pine in British Columbia.
other pine	red pine, Scots pine, pitch pine, and Austrian pine in eastern Canada, whitebark pine, ponderosa pine, and limber pine in British Columbia
hemlock	eastern hemlock in eastern Canada, western and mountain hemlock in British Columbia
larch	tamarack in all of Canada and alpine and western larch in Alberta and British Columbia
cedar, other conifers	cedar and other coniferous species.
unknown softwoods	no species differentation made.
trembling aspen	trembling aspen.
other poplar	poplar species other than trembling aspen.
yellow birch	yellow birch.
other birch	white, grey, and cherry birch.
sugar maple	sugar and black maple.
other maple	maple species other than sugar or black maple.
other broad-leaved	other deciduous species.
unknown hardwoods	no species differentation made.